

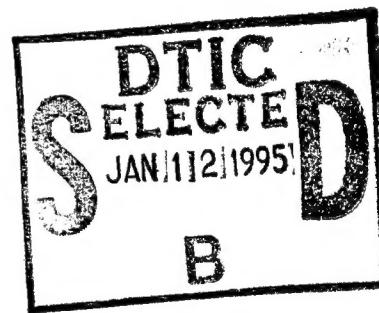
NATIONAL AIR INTELLIGENCE CENTER



ENGINEERING CALCULATIONS ASSOCIATED WITH THE
ABLATIVE THERMAL PROTECTIVE STRUCTURES OF RETURNABLE
SATELLITES

by

Xing Lianqun



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By: Xing Lianqun

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ENGINEERING CALCULATIONS ASSOCIATED WITH THE ABLATIVE THERMAL
PROTECTIVE STRUCTURES OF RETURNABLE SATELLITES

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Xing Lianqun

ABSTRACT

The paper describes one type of ablative thermal protective structure form associated with returnable satellites. It carries out discussions of ablation mechanisms and calculation methods associated with FL composite materials and silicone rubber. In conjunction with this, it carries out comparisons with flight tests and gives concluding opinions.

I. INTRODUCTION

Ablative thermal protection structures are forms which are efficient and provide relatively high heat protection. They have the greatest adaptability and are often used in returnable satellites.

Due to the limited nature of ground aerodynamic heat simulation tests, as far as studies of calculation methods for heat protection associated with ablative thermal protection structures are concerned, they then become extremely important.

China, in the late 1960's and early 1970's, then began studies of calculation methods for the ablative thermal protection of spacecraft. In conjunction with this, it obtained calculation results which marry up relatively well with ground heat simulation tests.

* Numbers in margins indicate foreign pagination.
Commas in numbers indicate decimals.

As far as the engineering calculations associated with ablative thermal protection structures are concerned, at the present time, there are two types of calculation methods which are commonly used. One type is designated as a decomposition surface method. Calculation formulae can be seen at 1 in the Appendices. It is recognized that, after satellite structure ablative materials have been heated, thermal decomposition takes place at a single temperature. This is also to say that, ablative materials take this temperature to make a boundary, dividing the zone of the carbon layer from the zone of the original material. In this way, it is possible to keep away from the complexities of pyrolytic or heat decomposition dynamics. Moreover, this makes the calculations simpler. With regard to the mass loss rates mp associated with pyrolytic gases, by contrast, one uses the heat conduction difference between the two sides of heat decomposition or pyrolytic surfaces in order to make

precise determinations. The classic case associated with this calculation method is seen in Reference [1]. Another type of calculation method is designated as a zone decomposition method. The calculation formulae can be seen at 2 in the Appendices. That is, recognizing them to be ablative materials, after being heated up, pyrolysis or heat decomposition takes place within one zone or region. This zone or region is defined from the two precise determinations of temperatures for the top and bottom. This type of calculation method is relatively complicated. As far as different types of ablative materials are concerned, it is necessary to make corresponding simplifying assumptions. Only then is it possible to realize the calculations. Classic cases can be seen in Reference [2]. Speaking in terms of numerical value calculations, the two types of calculation methods are both parabolic type partial differential equation sets associated with the solution of one dimensional dynamic boundaries. The treatments of this type of dynamic boundary are frequently a good deal of trouble to calculate. In particular, as far as the

amounts of sensitivity to these influences are involved, if one selects initial thicknesses for carbon layers, makes precise specifications for decomposition surface (zone) temperatures, gas mass loss rates mp , and boundary movement speeds, etc., and, if the values selected are inappropriate, then, in all cases, it will influence the accuracy of the calculation processes.

Attention should also be paid to rational selections for difference form choices, and the physical parameters of materials. This will also give rise to influences which cannot be ignored on calculation results.

Due to the universal expansion of computers, it is already possible at present to use the FORTRAN language in, micro computers, to realize design calculations for ablative thermal protection structures. /27

Thermal protection design work associated with ablative thermal protection structures, at the present time, are completely capable of being carried out by thermal design personnel themselves. At the same time, it is possible to make design personnel conveniently carry out optimization designs for thermal protection structures. It is also possible to begin the development of research work for the whole series of such influences as thermal and physical characteristics of materials on design results.

II. ANALYSIS OF ACTUAL CASES

The exterior shape of satellites as well as ablative structures are as shown in Fig.1. The status of heat received by them as well as ablative structures is as shown in Table 1.

As is shown in Table 1., the nose section of the satellite and the skirt section opt for the use of "FL composite materials

" + metal shell" structures. Base sections opt for the use of "silicone rubber ablative materials + metal shell" structures. Below, we carry out an elucidation of the ablative thermal protective mechanisms for these two types of structures respectively.

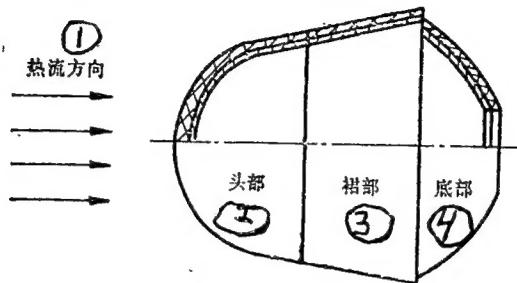


Fig.1 Schematic Diagram of Satellite Exterior Shape as well as Ablative Structures

Key: (1) Direction of Thermal Flow (2) Nose Section (3) Skirt Section (4) Base Section

TABLE 1 THE VARIOUS SATELLITE COMPONENT STRUCTURES AND THERMAL FLOW DISTRIBUTION

② 项目	⑥ 部 位	⑥ 头 部	⑦ 裙 部	⑧ 底 部
	烧蚀结构形式 ③	FL 复合材料 金属壳	烧蚀涂料 ⑨	金属壳 ⑩
④ 瞬时最大热流 q_{\max}	2 400 kW/m ²	460 kW/m ²	250 kW/m ²	
⑤ 总加热量 Q	12×10^7 J/m ²	2.8×10^7 J/m ²	1×10^7 J/m ²	

Key: (1) Component (2) Item (3) Ablative Structure Form (4) Instantaneous Maximum Thermal Flow q_{\max} (5) Total Amount of Heat Added (6) Nose Section (7) Skirt Section (8) Base Section (9) FL Composite Material/ Metal Shell (10) Ablative Coating/ Metal Shell

1. FL COMPOSITE MATERIAL + METAL SHELL STRUCTURE

This type of structure is the exterior surface of a metal shell and a definite thickness of FL composite material combined together into one body.

(1) FL Composite Materials Ablative Mechanisms [3]. The ablative mechanisms of FL ablative materials are capable of being divided into the several areas below:

(1) Thermal Breakdown or Pyrolysis of Materials. As far as the reception of heat by materials is concerned, when they reach a certain temperature, one then begins thermal decomposition or pyrolysis. Thermal decomposition or pyrolysis temperatures are determined on the basis of heat mass loss curves. After thermal decomposition or pyrolysis of materials, the gases produced will escape from the surface. When pyrolytic or heat decomposition gases pass over carbon layers, they will take along with them a portion of the amount of heat. At the same time, they will also produce mass induced emission effects. This effect is then capable of lowering the effects of convection adding heat. The entire thermal decomposition or pyrolysis process is a heat absorbing or endothermic reaction.

(2) Carbonization of Materials. After the heat decomposition or pyrolysis of materials, this carbon layer possesses a relatively small coefficient of heat conduction and a relatively high radiation coefficient. Because this is the case, besides giving rise to insulation effects, it is also capable of radiating to the outside large amounts of heat. The heat flow radiated to the outside is $q_2 = \epsilon \cdot \sigma \cdot T_w^4 \cdot 1$

Because this is the case, the higher the temperatures of carbon layer surfaces are, the larger are then the amounts of heat radiated to the outside. This process is also endothermic.

(3) Combustion of Surface Carbon Layers. When carbon layer surfaces reach a certain temperature, the carbon will burn.

The process of combustion is exothermic.

(4) Surface Recession. Due to the combustion of exterior surface carbon, surfaces will recede. If the carbon on the surface is unusually loose or porous, under the effects of aerodynamic forces, one will also have the occurrence of mechanical denuding or corrosion, making the surface recede.

(5) Conduction of Heat Inward.

(6) Pile Up of Carbon. After combustion, in carbon layers, one will have the occurrence of a phenomenon of carbon build up. This process will increase the density of carbon.

(2) Simplification of Calculation Models. The points of difference between decomposition surface calculation methods and decomposition zone calculation methods exist only in the former's taking decomposition zones and seeing them as surfaces. Because this is the case, with regard to the simplification of calculation models, the two are capable of being unified for purposes of description as follows (as far as the points of difference are concerned, they will be pointed out respectively):

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(1) One Dimensional Assumptions. It is recognized that the whole of the ablation and conduction processes occurs in a one dimensional space in all cases.

(2) Thermal Equilibrium Assumption. It is recognized that thermal decomposition or pyrolytic gases maintain local thermal equilibrium with residual carbon layers. Between them, there are no further chemical reactions.

(3) Induced Emission Effect Assumption. It is assumed that, as far as the mutual interactions between thermal decomposition or pyrolytic gases and boundary layer air are concerned, it is possible to use air-air induced emission effects in order to make descriptions and that there are no chemical reactions between them.

(4) Surface Recession Assumption. It is assumed that carbon layer surfaces have only surface recession given rise to by ablation. It is not necessary to consider recession which is given rise to by other factors (for example, mechanical denuding or corrosion).

(5) Decomposition Zone Calculation Method Assumption. As a prerequisite for the assumptions about the various items above, it is recognized that thermal decomposition or pyrolysis is carried out within a thermal decomposition or pyrolytic zone. The thermal decomposition or pyrolytic zone is precisely specified by the use of precise determinations of the upper and lower temperatures of the zone (see Fig.2). Within thermal decomposition or pyrolytic zones, the thermal and physical characteristic parameters associated with materials can be recognized to be functions of temperature.

(6) Decomposition Surface Calculation Method Assumption. Given the prerequisites of the four assumptions ((1)), ((2)), ((3)), and ((4)), it is recognized that, between carbon layers and the original materials, there exists an interior surface defined by a fixed temperature. In this way, a surface is designated as thermal decomposition or pyrolysis

surface. Using the thermal decomposition or pyrolysis surface for substitution with the thermal decomposition or pyrolysis zone, in this way, an assumption is designated as the decomposition or pyrolysis surface calculation method assumption.

(3) Discussion Relating to Decomposition Surface Calculation Methods. When the thickness of FL composite materials is 25mm, a comparison between temperature calculation results and satellite flight test results is seen in Fig.3.

Fig.2 Schematic Diagram of the Decomposition Zone Calculation Method Model

Key: (1) Original Surface
 (2) Ablation Zone
 (3) Carbon Layer Zone
 (4) Decomposition Zone
 (5) Original Material Zone
 (6) Back Wall Structure

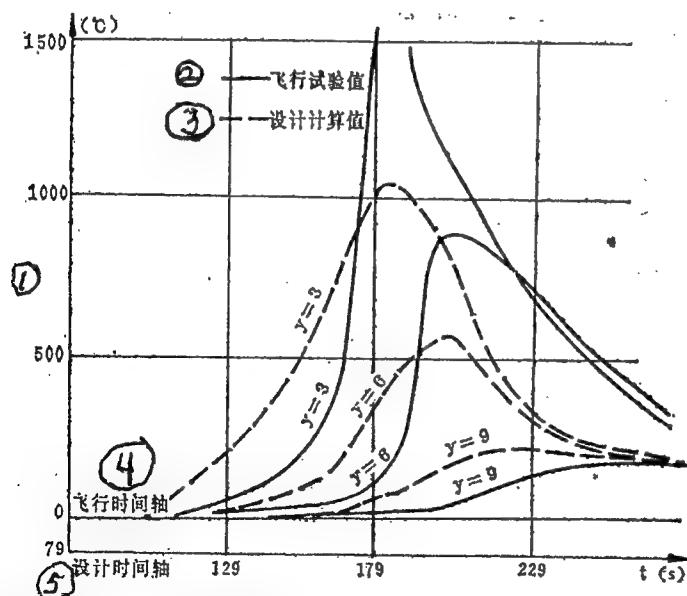
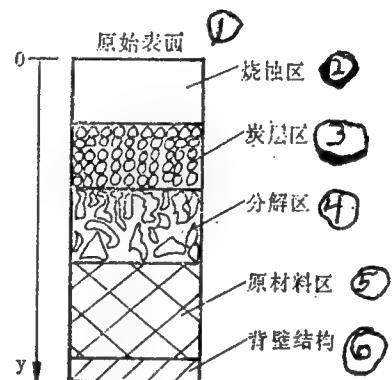


Fig.3 A Comparison of the Telemetry Results and Calculated Results for a Nose Section at a $\phi = 21^\circ$ Location

Key: (1) Temperature (2) Flight Test Values (3) Design Calculation Values (4) Flight Time Axis (5) Design Time Axis

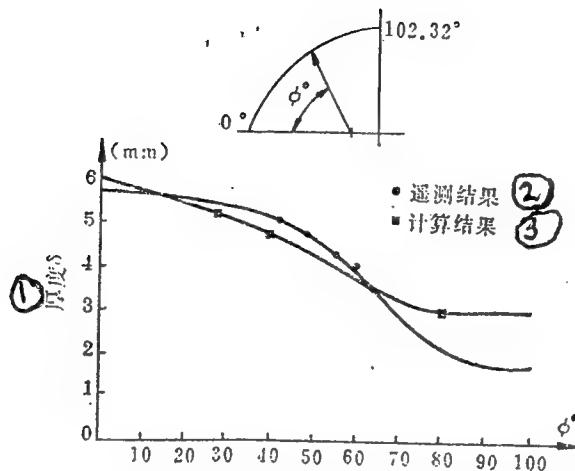


Fig.4 A Comparison of Nose Section Carbon Layer Thickness Design Results and Telemetry Data

Key: (1) Thickness (2) Telemetry Results (3) Calculation Results

Speaking in regard to nose sections, due to the fact that, during the processes of return, thermal flow is relatively high, material ablation occupies a leading role. Using decomposition surface calculation methods, it is possible to obtain results which marry up relatively well with flight test results (the higher thermal flows are in sections, the better they match up). See Fig.4. However, from Fig.3, it is possible to see that, as far as comparisons of flight tests and calculation results are concerned, calculation results for temperature tend to the low side on exterior surfaces. They tend to the high side on interior surfaces. The main reason for the calculation results on exterior surfaces tending to be low is that carbon layer thermal conduction coefficients used in calculations are greater

than actual thermal conductance coefficients. Moreover, the principal cause for inside surface temperatures tending to be high is one created by the use of decomposition surfaces to substitute for decomposition zones.

As far as skirt sections are concerned, due to the fact that thermal flows are relatively small, insulation plays the key role. In this type of situation, the effects of decomposition zones can then be ignored.

(4) Discussion Regarding Decomposition Zone Calculation Methods. Calculation models associated with decomposition zone calculation methods are as shown in Fig.2. Thermal protective systems as a whole are composed of a layer of heat protective material and several types of different back wall materials. Between the various layers of materials of the back walls, it is possible to have air spaces. It is also possible not to have air spaces. The thermal and physical parameters associated with various types of materials can be understood to be functions of temperature. Other assumptions are as described in (2). On the basis of these fundamental calculation formulae, decomposition zone calculation method programs were written.

Using the programs written, calculations were carried out for nose sections and skirt sections. The results of temperature calculations matched up when compared with flight test results. See Fig.5 and Fig.6.

2. SILICONE RUBBER ABLATION MATERIAL + METAL SHELL STRUCTURES

Silicone rubber ablation coating takes silicone rubber as a base. It adds in, at given ratios, polyethylene and composite short fibers as well as the corresponding binders and promoting

agents for its formation. Taking the coating and spreading it on the exterior surface of metal shells, one, then, forms ablation coating type thermal protection structures. This type of /30 ablation coating possesses relatively good ablation properties and insulation properties. It is appropriate for use in situations where heat is added over relatively long periods as low grade thermal flows.

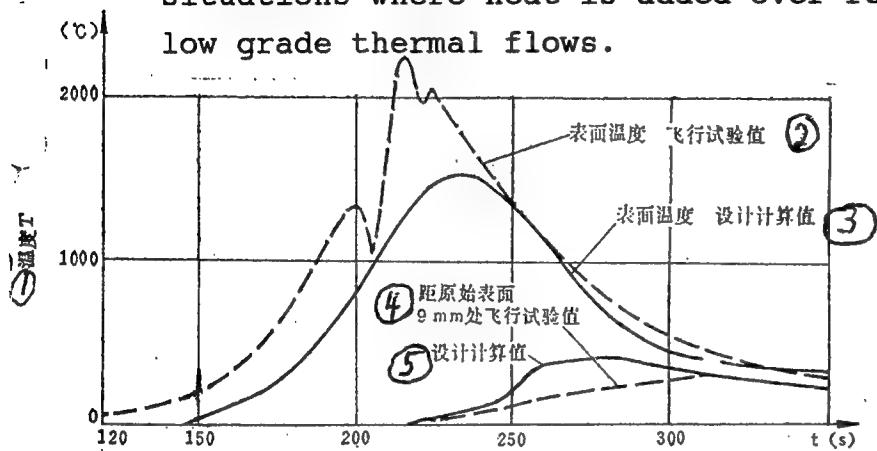


Fig.5 Nose Section Temperature Change Curves

Key: (1) Temperature (2) Surface Temperature Flight Test Values (3) Surface Temperature Design Calculation Values (4) Flight Test Values for Location 9mm Away From Original Surfaces (5) Design Calculation Values (6) Time

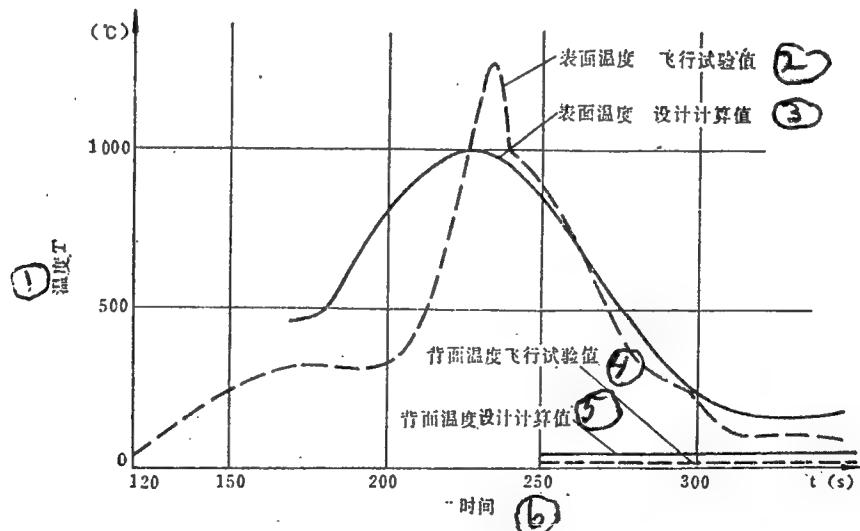


Fig.6 Skirt Section Surface and Back Surface Temperature Curves

Key: (1) Temperature (2) Surface Temperature Flight Test Values (3) Surface Temperature Design Calculation Values (4) Back Surface Temperature Flight Test Values (5) Back Surface Temperature Design Calculation Values (6) Time

(1) Silicone Rubber Ablation Coating Ablation Mechanisms. Silicone rubber ablation coatings also belong to the carbonization class of ablation materials. Because this is the case, there are no differences in principle between their ablation mechanisms and the general run of carbonization ablation materials. However, silicone rubber coatings also have a number of special points. First of all, during ablation processes, materials will show the occurrence of expansion. This is shown clearly by tests. When the coating thickness is 3-4 mm, generally speaking, there will be expansion of 2-4 mm in all cases. Secondly, carbon layer structures are also relatively complicated. When heat flows are relatively large, tests clearly show that, on surfaces, there will be produced a hard shell which has a loose and brittle texture. The lower surface is a layer possessing a number of powdery half air pocket structures. Again, lower surfaces are expansion layers. On the lower surface of the expansion layers, by contrast, are intact silicone rubber coating layers. Looking at everything as a whole, the portion of structures which belong to carbon layers are relatively complicated.

(2) The Simplification of Calculation Models. Due to the fact that the mechanisms of heat exchange associated with the half air pocket structure, which is formed by the double splitting of silicone rubber, are still unclear, as a result of this, calculation assumptions are also very crude.

Opting for the use of decomposition surface calculation methods, simplification assumptions are the same as the various items ((1)), ((2)), and ((3)) in (2) discussed above. Besides this, in a general model of carbonizing ablation, surfaces recede in all cases. However, in the processes of the ablation of silicone rubber, expansion is a primary factor. Because this is the case, one need not consider surface recession which is given rise to by the combustion of carbon.

As far as the expansion of silicone rubber is concerned, one need only give consideration to its surface temperature functions (see Fig.7). For calculation model see Fig.8.

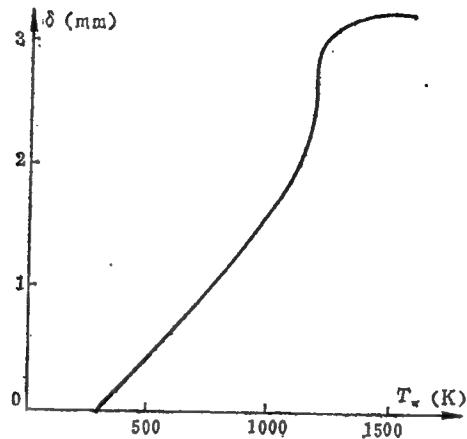


Fig.7 Change Curves for Expansion Layer Thickness δ Following Along with Surface Temperature T_w

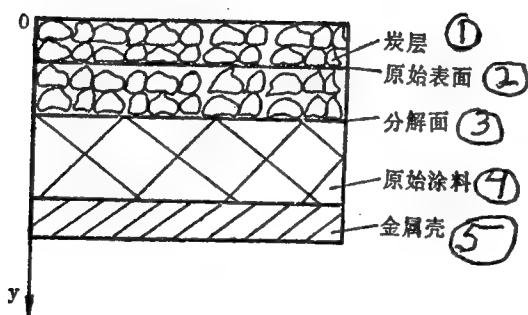


Fig.8 Silicone Rubber Coating Ablation Calculation Model

Key: (1) Carbon Layer (2) Original Surface (3) Decomposition Surface (4) Original Coating (5) Metal Shell

(3) Discussion Concerning Silicone Rubber Ablation Coating Calculation Methods. The section after decomposition of silicone rubber is generally known as the carbon layer. The heat conduction coefficient for this section is very difficult to actually measure. Because this is the case, the key to calculations rests in how the thermal conduction coefficients for carbon layer zones are selected. On the basis of analysis of results from surface tests, one makes the assumptions that follow: that is, taking carbon layers and dividing them into two sections, inside the expansion layer close to the decomposition surface, it is filled with thermal decomposition or pyrolytic gases. The coefficients of thermal conductance are relatively low. It is recognized that the thermal conductance coefficients are relatively close to the thermal conductance coefficients associated with air in the same range of temperatures. This value is selected as $0.84 \times 10^{-4} \text{ kW/m}\cdot\text{K}$. The upper surface of this layer is a loose, porous layer of carbon. The heat conductance coefficient will be larger than the heat conductance coefficient of the original material. Values are chosen as 1.5 times the original material.

After going through these kinds of assumptions, option is made for the use of decomposition surface calculation methods. The calculation results are shown in Table 2.

The metal shell back surface temperatures measured in flight tests are $T_B \leq 470 \text{ K}$. The maximum temperature for T_B calculated results is 505 K. Giving consideration to the influences of the heat flows sustained by the base sections and errors in the set up of the flows as well as other factors, it is possible to recognize that calculation results and measured results marry up relatively well.

TABLE 2 TEMPERATURE DISTRIBUTIONS AT DIFFERENT INSTANTS FOR ABLATION COATING STRUCTURES

① 时间 t (s)	② 表面温度 T (K)	③ 金属壳背面温度 T_B (K)	隔热材料背面温度 T_C (K)	④
$t_0 = 159$	300	300	300	
$t_{q\max} = 231$	775	471	300	
$t_{T\max} = 233$	781	474	300	
$t_{TB\max} = 268$	465	505	300	
$t_{Tc\max} = 289$	453	495	300	

⑤ 注: t_0 一起始时间; $t_{q\max}$ —最大热流时间; $t_{T\max}$ —最高表面温度时间; $t_{TB\max}$ —金属壳背面最高温度时间; $t_{Tc\max}$ —隔热材料背面最高温度时间。

Key: (1) Time (2) Surface Temperature (3) Metal Shell Back Surface Temperature (4) Insulation Material Back Surface Temperature (5) Note: t_0 is time of origin; $t_{q\max}$ is maximum thermal flow time; $t_{T\max}$ is maximum surface temperature time; $t_{TB\max}$ is metal shell back surface maximum temperature time; $t_{Tc\max}$ is insulation material back surface maximum temperature time.

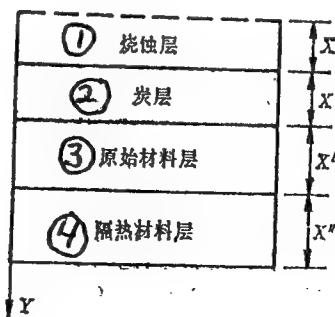
III. APPENDICES

1. DECOMPOSITION SURFACE ALGORITHM CALCULATION PROCESSES

Coordinate relationships (see Fig.9):

Fig.9 Decomposition Surface Algorithm Coordinate Relationships

Key: (1) Ablation Layer
 (2) Carbon Layer
 (3) Original Material Layer
 (4) Insulation Material Layer



$$\bar{X} = \int_0^t \frac{\dot{m}_e}{\rho} dt \quad (1)$$

$$X = X_0 + \int_0^t \frac{\dot{m}_p}{\rho' - \rho} dt - \int_0^t \frac{\dot{m}_e}{\rho} dt \quad (2)$$

$$X' = X'_0 - \int_0^t \frac{\dot{m}_p}{\rho' - \rho} dt \quad (3)$$

$$X'' = X''_0 \quad (4)$$

Equations:

$$\frac{\partial}{\partial Y} \left(k \frac{\partial T}{\partial Y} \right) + \dot{m}_p \cdot c_p \frac{\partial T}{\partial Y} = \rho \cdot c_p \frac{\partial T}{\partial t} \quad (\bar{X} \leq Y \leq \bar{X} + X) \quad (5)$$

$$\frac{\partial}{\partial Y} \left(k' \frac{\partial T'}{\partial T} \right) = \rho' \cdot c_{p'} \cdot \frac{\partial T'}{\partial t} \quad (\bar{X} + X \leq Y \leq \bar{X} + X + X') \quad (6)$$

$$\frac{\partial}{\partial Y} \left(k'' \frac{\partial T'}{\partial Y} \right) = \rho'' \cdot c_{p''} \cdot \frac{\partial T''}{\partial t} \quad (\bar{X} + X + X' \leq Y \leq X_0 + X'_0 + X''_0) \quad (7)$$

Original conditions:

$$T(Y, 0) = q(Y) = \text{常值} \quad (8)$$

Boundary conditions:

Carbon layer surface:

$$Y = X \quad (9)$$

$$\psi q_0 + q_R - \varepsilon \cdot \sigma \cdot T_w^4 + \dot{m}_e \cdot \Delta h_e + k \frac{\partial T}{\partial Y} = 0$$

Thermal decomposition or pyrolytic surface:

$$Y = \bar{X} + X \quad (10)$$

$$\begin{cases} T = T_s \\ -k \frac{\partial T}{\partial Y} = \dot{m}_p \cdot \Delta h_p - k' \frac{\partial T'}{\partial Y} \end{cases}$$

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When $T_{Y-\bar{X}+X} < T_s$

$$\dot{m}_p = 0 \quad (11)$$

The common boundary surface between original materials and insulation materials is $Y = \bar{X} + X + X'$

$$\begin{cases} T' = T'' \\ -k' \frac{\partial T'}{\partial Y} = -k'' \frac{\partial T''}{\partial Y} \end{cases} \quad (12)$$

The insulation material back surface $Y = \bar{X} + X + X' + X''$

$$\frac{\partial T''}{\partial Y} = 0$$

or

$$-k'' \frac{\partial T''}{\partial Y} = \epsilon'' \cdot \sigma \cdot [T_{Y-\bar{X}-X-X'-X''} - T_b^4] \quad (13)$$

2. DECOMPOSITION ZONE ALGORITHM CALCULATION PROCESSES

Coordinate relationships (see appended Fig.10):

$$\bar{X} = X_0 + \int_0^t \frac{\dot{m}_p}{\rho} dt \quad (14)$$

$$X = Y_{T-T_{g1}} - \bar{X} \quad (15)$$

$$X' = Y_{T-T_{g2}} - \bar{X} - X \quad (16)$$

$$X'' = X''_0 - (\bar{X} + X + X') \quad (17)$$

$$X''' = X'''_0 \quad (18)$$

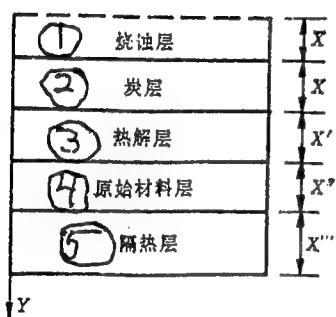


Fig.10 Decomposition Zone Algorithm Coordinate Relationships

Key: (1) Ablation Layer (2) Carbon Layer (3) Heat Decomposition or Pyrolytic Layer (4) Original Materials Layer (5) Insulation Layer

$$\frac{\partial}{\partial Y} \left(k \cdot \frac{\partial T}{\partial Y} \right) + \dot{m}_p \cdot \bar{c}_p \cdot \frac{\partial T}{\partial Y} = \rho \cdot c_p \frac{\partial T}{\partial t} \quad \bar{X} \leq Y \leq \bar{X} + X$$

Equations:

$$\frac{\partial}{\partial Y} \left(k' \frac{\partial T'}{\partial Y} \right) + \dot{m}_p' \cdot \bar{c}_p' \frac{\partial T'}{\partial Y} = \rho' \cdot c_p' \frac{\partial T'}{\partial t} - \Delta H_p \cdot \dot{w}_p \quad \bar{X} + X \leq Y \leq \bar{X} + X + X' \quad (19)$$

(20)

$$\dot{\omega}_p = \frac{\partial \rho'}{\partial t}$$

In this

$$\rho'' \cdot c_p'' \frac{\partial T''}{\partial t} = \frac{\partial}{\partial Y} \left(k'' \frac{\partial T''}{\partial Y} \right) \quad \bar{X} + X + X' \leq Y \leq X''_0 \quad (21)$$

$$\rho''' \cdot c''' \cdot \frac{\partial T'''}{\partial t} = \frac{\partial}{\partial Y} \left(k''' \frac{\partial T'''}{\partial Y} \right) \quad X_0'' \leq Y \leq X_0''' \quad (22)$$

Original conditions:

$$T(Y, 0) = g(Y) = \text{Constant Value}$$

Boundary conditions:

$$\text{Carbon layer surface} \quad Y = \bar{X}$$

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$$\Psi \cdot q_0 + q_R - \varepsilon \cdot \sigma \cdot T_w^4 + m_c \cdot \Delta h_c + k \frac{\partial T}{\partial Y} = 0 \quad (23)$$

Common boundary surface of carbon layer and thermal decomposition or pyrolytic layer $Y = \bar{X} + X$

$$\begin{cases} T = T' = T_{s1} \\ -k' \frac{\partial T'}{\partial Y} = -k \frac{\partial T}{\partial Y} \end{cases} \quad (24)$$

Common boundary surface of thermal decomposition or pyrolytic layer and original material $Y = \bar{X} + X + X'$

$$\begin{cases} T = T'' = T_{s2} \\ -k' \frac{\partial T'}{\partial Y} = -k'' \frac{\partial T''}{\partial Y} \end{cases} \quad (25)$$

Common boundary surface of original material and insulation material $Y = X''_0$

$$\begin{cases} T'' = T''' \\ -k'' \frac{\partial T''}{\partial Y} = -k''' \frac{\partial T'''}{\partial Y} \end{cases} \quad (26)$$

Insulation material back surface $Y = X''_0 + X_0'''$

$$\frac{\partial T'''}{\partial Y} = 0$$

$$\text{or} \quad -k''' \frac{\partial T'''}{\partial Y} = \varepsilon''' \cdot \sigma [T^4_{y=x''_0+x'''_0} - T_b^4] \quad (27)$$

3. EXPLANATION OF SYMBOLS

An explanation of the different meanings of symbols is seen in Table 3.

TABLE 3 EXPLANATION OF SYMBOLS WITH DIFFERENT MEANINGS

(1) 符号	(2) 分解面算法中的含义	(3) 分解区算法中的含义
x'	(4) 原材料厚度	(12) 分解区材料厚度
x''	(5) 隔热材料厚度	(13) 原材料厚度
x'''		(14) 隔热材料厚度
ρ'	(6) 原材料密度	(15) 分解区材料密度
ρ''	(7) 隔热材料密度	(16) 原材料密度
ρ'''		(17) 隔热材料密度
k'	(8) 原材料导热系数	(18) 分解区材料导热系数
k''	(9) 隔热材料导热系数	(19) 原材料导热系数
k'''		(20) 隔热材料导热系数
c_p'	(10) 原材料比热	(21) 分解区材料比热
c_p''	(11) 隔热材料比热	(22) 原材料比热
c_p'''		(23) 隔热材料比热

Key: Meaning in Decomposition Zone Algorithm (4) Original Material Thickness (5) Insulation Material Thickness (6) Original Material Density (7) Insulation Material Density (8) Original Material Thermal Conduction Coefficient (9) Insulation Material Thermal Conduction Coefficient (10) Original Material Specific Heat (11) Insulation Material Specific Heat (12) Decomposition Zone Material Thickness (13) Original Material Thickness (14) Insulation Material Thickness (15) Decomposition Zone Material Thickness (16) Original Material Density (17) Insulation Material Density (18) Decomposition Zone Material Thermal Conduction Coefficient (19) Original Material Thermal Conduction Coefficient (20) Insulation Material Thermal Conduction Coefficient (21) Decomposition Zone Material Specific Heat (22) Original Material Specific Heat (23) Insulation Material Specific Heat

Explanations for symbols with the same meanings are seen in Table 4.

TABLE 4 EXPLANATION OF SYMBOLS WITH THE SAME MEANINGS

(1) 符号	(2) 符号含义	(1) 符号	(2) 符号含义
\bar{X}	(3) 烧蚀层厚度	Ψ	阻塞效应系数 (15)
X	(4) 炭层厚度	ε''	隔热材料辐射系数 (16)
ρ	(5) 炭层密度	ε'''	隔热材料辐射系数 (17)
K	(6) 炭层导热系数	ε	材料辐射系数 (18)
c_p	(7) 炭层比热	σ	斯蒂芬-波尔兹曼常数 (19)
\dot{c}_p	(8) 热解气体比热	Δh_c	每单位质量炭的燃烧热 (20)
\dot{m}_c	(9) 炭层质量损失率	Δh_p	热解热 (21)
\dot{m}_p	(10) 非炭材料损失率	T_b	舱内环境温度 (22)
t	(11) 时 间	T_g	分解面温度 (23)
T	(12) 温 度	T_{g1}	炭层与分解区交界面温度 (24)
q_o	(13) 对流加热热流率	T_{g2}	原材料与分解区交界面温度 (25)
q_R	(14) 辐射加热热流率		

Key: (1) Symbol (2) Symbol Meaning (3) Ablation Layer Thickness (4) Carbon Layer Thickness (5) Carbon Layer Density (6) Carbon Layer Thermal Conduction Coefficient (7) Carbon Layer Specific Heat (8) Thermal Decomposition or Pyrolytic Gas Specific Heat (9) Carbon Layer Mass Loss Rate (10) Non-Carbon Material Loss Rate (11) Time (12) Temperature (13) Convective Heating Thermal Flow Rate (14) Radiant Heating Thermal Flow Rate (15) Blocking Effect Coefficient (16) Insulation Material Radiation Coefficient (17) Insulation Material Radiation Coefficient (18) Material Radiation Coefficient (19) Steven-Bortzmann (phonetic) Constant (20) Combustion Heat Associated with Each Unit Mass of Carbon (21) Heat of Thermal Decomposition or Pyrolytic Heat (22) Ambient Temperature in Cabin (23) Decomposition Surface Temperature (24) Temperature on Common Surface of Carbon Layer and Decomposition Zone (25) Temperature on Common Surface of Original Material and Decomposition Zone

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